Global EFT Fits at Future Colliders

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with the help of
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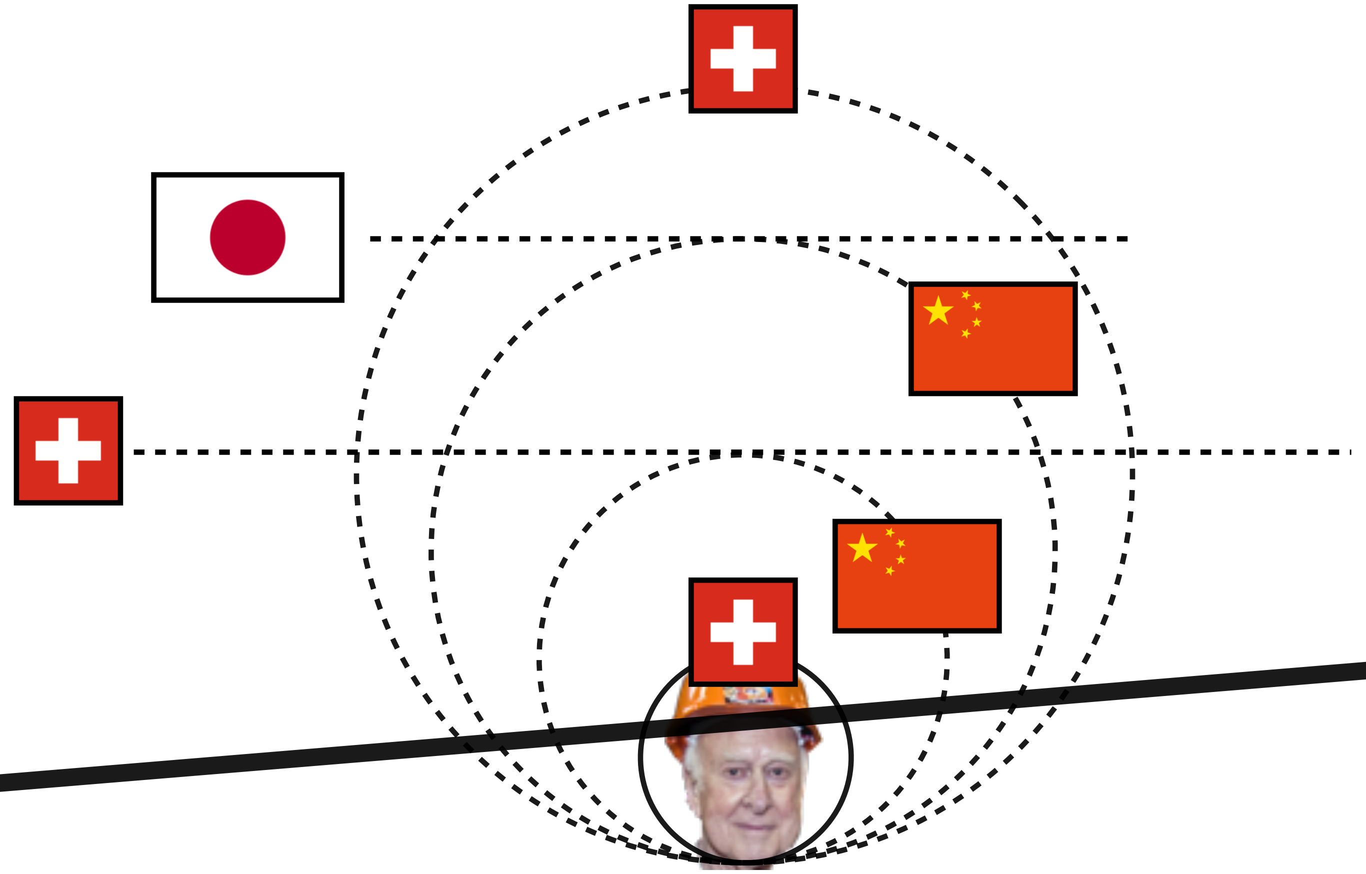


Global EFT Fit

include not only Higgs but also top, di-boson and EWK precision observables

- No 4-quark operators (4-lepton operators affect G_F) since they are better constrained outside Higgs processes, except maybe for the top (but not considered yet, see Eleni's presentation).
- No RH-currents (chiral suppression).
- No dipole operators (chiral suppression in production, contribution only to 3-body decays). Top dipoles could be relevant but neglected for now.
- Flavour assumptions
  - flavour universality: 19 independent parameters + 5 SM inputs
  - flavour diagonality: 31 independent parameters + 5 SM inputs

working at linear-level in the EFT effects

Experimental Inputs

A circular ee Higgs factory starts as a Z/EW factory (**TeraZ**)

A linear ee Higgs factory operating above Z-pole can also preform EW measurements via **Z-radiative** return

A linear ee Higgs factory could also operate on the Z-pole though at lower lumi (**GigaZ**)

	Higgs	aTGC	EWPO	Top EW
FCC-ee	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom.)	Yes	Yes (365 GeV, Ztt)
ILC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (HE limit)	Yes (Rad. Return, Giga-Z)	Yes (500 GeV, Ztt)
CEPC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom)	Yes	No
CLIC	Yes (μ, σ_{ZH})	Yes (Full EFT parameterization)	Yes (Rad. Return, Giga-Z)	Yes
HE-LHC	Extrapolated from HL-LHC	N/A → LEP2	LEP/SLD + HL-LHC (M_W, $\sin^2\theta_W$)	-
FCC-hh	Yes (μ, BR_i/BR_j) Used in combination with FCCee/eh	From FCC-ee	From FCC-ee	-
LHeC	Yes (μ)	N/A → LEP2	LEP/SLD + HL-LHC (M_W, $\sin^2\theta_W$)	-
FCC-eh	Yes (μ) Used in combination with FCCee/hh	From FCC-ee	From FCC-ee + Zuu, Zdd	-

Bases of dim-6 Operators

$$\mathcal{O}_6 = -\lambda\,|H|^6$$

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{q}_L H u_R + \text{h.c.}$
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{q}_L H d_R + \text{h.c.}$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{l}_L H e_R + \text{h.c.}$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}'_{H\ell} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$
$\mathcal{O}_{\ell\ell} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$	$\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$
$\mathcal{O}_{Hq} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L$	$\mathcal{O}_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R \gamma^\mu u_R$
$\mathcal{O}'_{Hq} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \sigma^a \gamma^\mu q_L$	$\mathcal{O}_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R \gamma^\mu d_R$

- SILH' basis (eliminate $\mathcal{O}_{WW}$, $\mathcal{O}_{WB}$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Modified-SILH' basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Warsaw basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{HW}$ and $\mathcal{O}_{HB}$)

- Flavour assumptions
  - flavour universality: 19
  - flavour diagonality: 31-33

c, b, t, μ, τ Yukawa only
U(2) symmetry
among 2 first quark generations

BR_{inv} and $\text{BR}_{\text{untagged}}$
to take into account
light quark generations

Effective Higgs Couplings from EFT Fits

EFT fits can be performed in different bases (difficult to compare results among different analyses) and seldom the meaning on the sensitivity on the various Wilson coefficients is transparent

— Practical approach —

perform the fit in any basis you like and project the results on **effective/pseudo couplings**

(need a special care for top coupling and self-coupling)

$$g_{HX}^{\text{eff}\ 2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\text{SM}}}$$

Effective Higgs couplings

Similar definition as κ modifiers, but different interpretation, e.g.

$$\frac{\Gamma_{ZZ^*}}{\Gamma_{ZZ^*}^{\text{SM}}} \simeq \underline{1 + 2\,\delta c_Z} - 0.15\,c_{ZZ} + 0.41\,c_{Z\Box} + \ldots \text{ (EW } Vff,\ hVff\text{)}$$

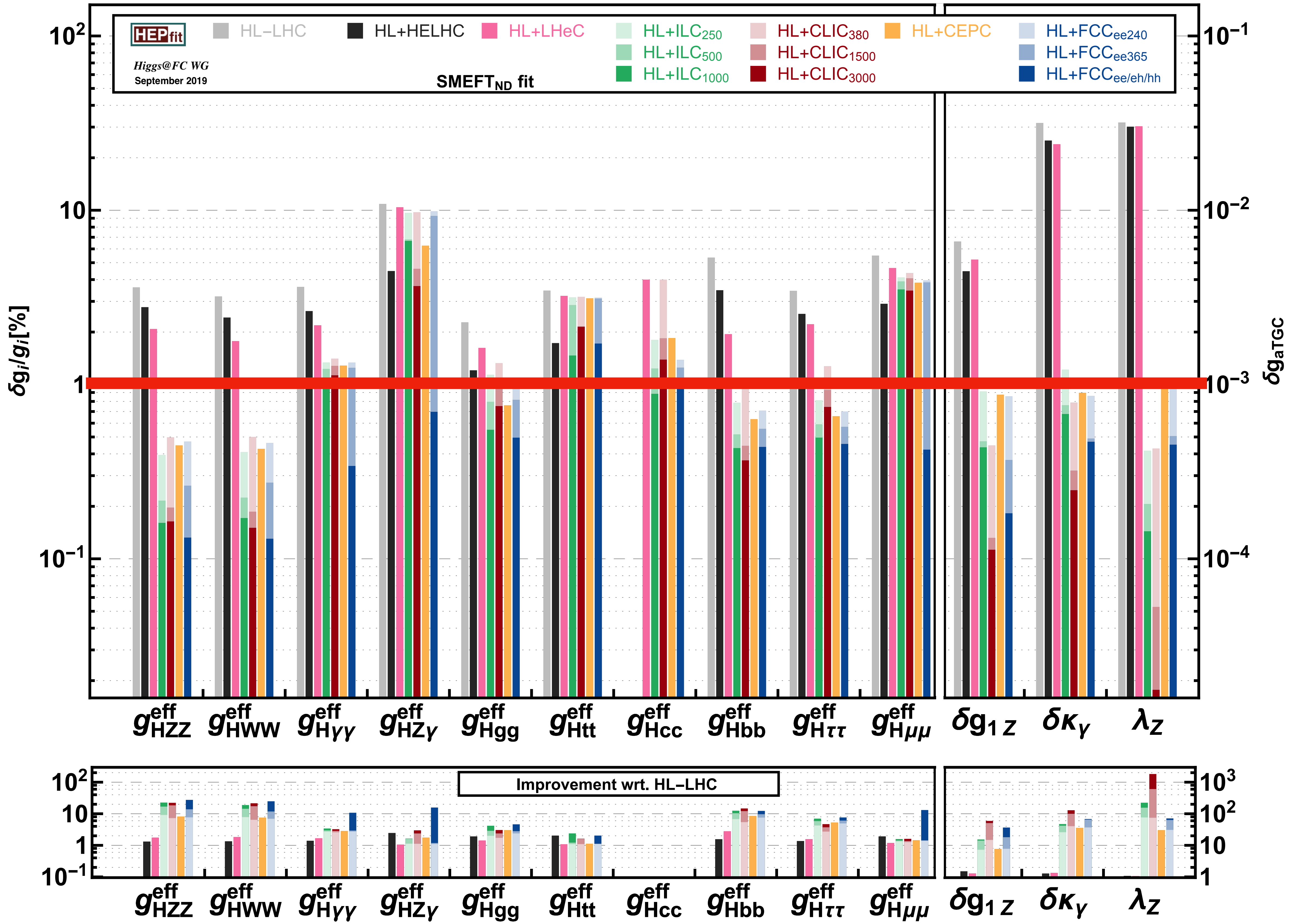
Only these are described in κ-framework

Not enough to match EFT d.o.f : Add also aTGC

Similarly, for EW interactions, **project results into effective *Zff* couplings** defined from EWPO, e.g.

$$\Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w \cos^2\theta_w}(|g_L^e|^2 + |g_R^e|^2), \qquad A_e = \frac{|g_L^e|^2 - |g_R^e|^2}{|g_L^e|^2 + |g_R^e|^2}$$

Global EFT Fit



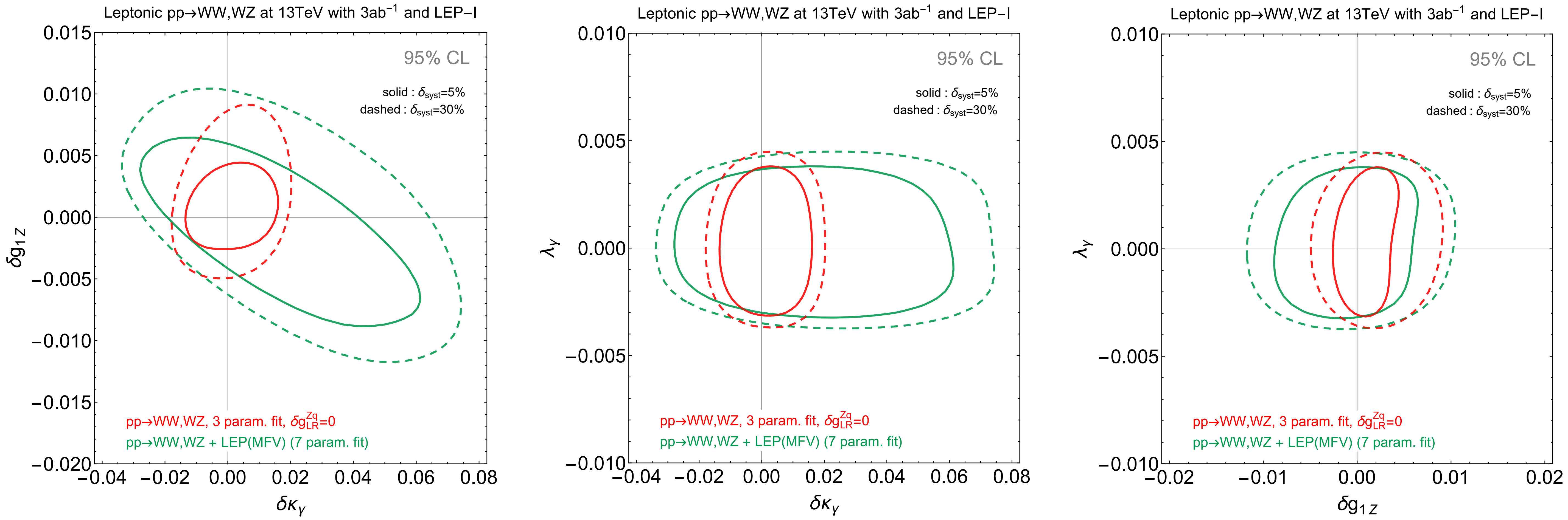
ECFA Higgs study group '19

1% threshold

About VBS channels

At LEP, diboson channels were mostly analysed in terms of TGC.
At LHC, and future hadron colliders, often TGC dominance assumption (fit with 3 TGCs only) is made.
Full EFT analysis, with optimal observables in particular (→ see J. Gu's talk on Thursday), can be quite different: flavour assumptions can play a big role too!

Grojean, Montull, Riembau '18



TGC dominance ≈ Flavour Universal ≠ Minimal Flavour Violation Scenarios

No global EFT analysis with generic flavour assumption available yet!

Future Directions - I

inclusive measurements vs kinematical distributions accessible
at either leptonic machines (thanks to clean environment) or high-energy hadronic machines

- Higgs couplings at high-energy (relying on STXS?)
  1. off-shell $gg \to h^* \to ZZ \to 4l$,
  2. boosted Higgs: Higgs + high-p_T jet,
  3. VH at large invariant mass (double differential distributions sometime needed to restore BSM/SM interference).

- High pT distribution**: “energy helps accuracy” (☞ beware of EFT validity)

  1. BSM effects often grow with energy,
  2. study of poorly populated phase space regions with smaller systematics.

- NLO effects: include the most precise predictions when available, but be careful, NLO could introduce more parameters and prevent the fit from closing, so extra measurement/data might be needed.

* *some pheno projections were implemented in the ECFA SILH fit:
di-fermions prod., ZH(bb), WZ at high-invariant mass but no full EFT analysis available yet.

Future Directions - II

- Estimate EFT uncertainties (NLO, dim-8 effects, linear vs quadratic…), NP in backgrounds, theoretical constraints (positivity, analyticity), SMEFT vs. HEFT… → see G. Durieux's talk on Thursday
- Explore more flavour scenarios (and make connection with flavour data)
- Full-fledged EFT analysis of diboson data (away from TGC dominance assumption) with statistically optimised observables
- More combined Higgs and top analysis → see next talk by E.Vryonidou
  1. effects of top dipoles or 4 fermion ops. with tops
  2. constraints on top EW couplings from their NLO effects in Higgs and diboson processes (particularly relevant for low-energy colliders below ttH threshold)
- Generalisation of (pseudo)-observables to report EFT fits
  1. give justice to differential measurements
  2. well suited for a global approach with H, EW, top, flavour
- Don't forget correlations
- Provide more BSM interpretations, i.e., match to different models/UV dynamics. Which physics hypotheses do we want to test? Which consequences for cosmo?